Deformation Analysis of the Holcim Ltd. Cement Factory Objects

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Key words: shift, deformation, deformation analysis, stable and unstable point.

SUMMARY

The paper presents theoretical bases of deformation analysis according to the models Hannover and Karlsruhe. Their practical application has been checked on the results of measuring the vertical movements of silos for concrete storage in the factory Holcim d.o.o. in Koromačno. The vertical movements on the silo have been measured in three series. For each measurement series there has been a deformation analysis carried out for the purpose of determining possible movements. The application of deformation models was to result in defining which points remain stable, and unstable points should be localised. The comparison of stated methods would define whether there are any essential differences among them in discovering unstable points and which method is better and more practical to be applied.

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1. INTRODUCTION

The determination of movements and deformations of construction objects is one of the most demanding geodetic tasks. It is necessary to determine the stability of objects at the moment of their erecting, and later in the exploitation phases. Namely, due to various influences (geologic and hydrological changes), the change of atmospheric conditions (temperature, pressure and humidity), the change of mechanical properties of the material that the objects are made of, and due to various loads certain movements and deformations of objects can appear.

Movement is a spatial change of the position of some point on the object or the ground between two or more measurements series. We can monitor the movements by observing the positions of individual points on the objects from the points outside of the object, and we determine the deformation on the basis of the results of movements of a series of points. Each object that we want to monitor continuously needs to be idealized by a certain number of points. These points and the network of points outside of the zone of possible deformation make a unit for movement measurement.

The main problem during the movement measurement in some network, i.e. of the deformation analysis (Kapović 1993) is: how to determine which points remain stable between more measurement series? Hence, the deformation analysis deals with the problem of determining stable points in the network, i.e. of localising unstable points.

2. THEORETICAL BASES OF DEFORMATION ANALYSES

There is a larger number of methods dealing with deformation analysis. Searching for an optimal method in discovering a movement used to present a great challenge for various research centres, researchers and groups. Every suggested method, approach or school had different presumptions, mathematical models and statistical analyses.

In the period of eight years the FIG Commission 6 was dealing with the deformation analysis methods in order to conclude which method was the best and the most practical to be applied. In its report it was concluded that in spite of a large number of similarities existing among various deformation model it is very difficult to choose the best one or to suggest one general approach to deformation analysis. The final selection of deformation analysis model is left therefore to users (Chrzanowski, Chen 1986).
This paper presents the application of two deformation analysis models: Hannover and Karlsruhe model.

2.1 Deformation Analysis according to Hannover Model

The deformation analysis according to the Hannover model, i.e. the determination of stable points between two or more series of measurements should be solved in five phases:

1. Adjustment of individual measurement series,
2. testing of homogeneity of measurements between the series,
3. determination of global movements between two series (*zero and i*-th) of measurements,
4. movement localization, i.e. identifying unstable points outside of objects, and
5. movement localization, i.e. identifying unstable points on an object.

The method is based upon the testing of the congruity of the coordinates of points in two or more measurement series obtained by network adjustment for each measurement series independently. The adjustment of a single measurement series is done according to the method of least squares with minimal trace of coordinate cofactor matrix:

$$v^T P v = \min\ ,\ x^T x = \min\ .$$

After that it should be determined whether the measurements in all series are of equal accuracy, i.e. whether they are *homogeneous*. From the adjustment of two series the empirical variances ${\sigma_1}^2$ and ${\sigma_2}^2$ are obtained, and their equality should be determined with adequate probability, which results in finding out whether both measurement series have homogeneous accuracy. For this purpose the zero and alternative hypotheses are given:

$$H_0{:}E\left(\sigma_1^2\right) = E\left(\sigma_2^2\right) = \sigma^2\ ,$$
$$H_A{:}E\left(\sigma_1^2\right) \neq E\left(\sigma_2^2\right) \neq \sigma^2\ .$$

The acceptance of zero hypothesis H_0 means that the series of measurements are homogenous, and the acceptance of alternative hypothesis H_A means that the series of measurements are of non-homogeneous accuracy. If the measurement series are not homogeneous, it is necessary to make homogenisation of measurement.

By global analysis of movements we determine whether there has been any significant movement of points in the geodetic network between two measurement series (Pelzer 1971, Niemeier 1976, 1985). The congruence of the network can be tested by means of adequate tests of mathematical statistics. One sets the zero-hypothesis and alternative hypothesis, i.e. one needs to test whether the unknowns of measurements in two series are equal (Pelzer 1985):

$$H_0{:}E\left(\hat{x}_1\right) = E\left(\hat{x}_2\right), d = \hat{x}_i - \hat{x}_1 = 0 \Rightarrow H_0{:}E\left(d\right) = 0,$$
$$H_A{:}E\left(\hat{x}_1\right) \neq E\left(\hat{x}_2\right), d = \hat{x}_i - \hat{x}_1 = 0 \Rightarrow H_A{:}E\left(d\right) \neq 0,$$

where:
- $\hat{x}_1, \hat{x}_i$ - are estimated vectors of the unknowns in the *zero* and *i-th* measurement series,
- d - is the vector difference of coordinates.

Accepting the zero hypothesis H_0 means that the coordinates of points are congruent in both sereis, and accepting H_A means that the points have not retained the same position in the period between two series. Test statistics is calculatged according to:

$$F = \frac{\theta^2}{\sigma^2},\ \theta^2 = \frac{\hat{d} Q_{\hat{d}}^{+} \hat{d}}{h},\ \sigma^2 = \frac{f_1 \sigma_1^2 + f_2 \sigma_2^2}{f_1 + f_2},$$

where:

- $h = rang Q_{\hat{d}}$ - is a rang cofactor matrix of coordinate difference,
- $Q_{\hat{d}}^{+}$ - pseudo inversion of the cofactor matrix of coordinate difference.

For the selected level of reliability $(\alpha = 0{,}05)$ and the number of freedom degrees, the theoretical value $F_{1-\alpha,h,f}$ is read from the table available on Internet (URL1). When the value of test statistics is smaller than the critical value:

$$F \leq F_{1-\alpha,h,f}$$

the zero hypothesis is accepted, which means that the coordinates of points from both series are congruent. When the value of test statistics is larger than the critical value, the alternative hypothesis is accepted, i.e. the coordinates of points are not congruent. Presuming that the points of the fundamental network are stable, one should designate whether there has been any movement of points on the object.

For the purpose of testing the movements of points on the object, the movement vector is divided into sub-vectors (Savšek-Safić 2002):

$$\hat{d} = \begin{pmatrix} \hat{d}_F \\ \hat{d}_o \end{pmatrix},$$

where the coordiantes differences of fundamental points identified as stable points are listed into the vector $\hat{d}_F$, the coordinates differences of points on the object into the vector $\hat{d}_O$. In accordance with this classification, the cofactor matrix of the differences of coordinates is divided into sub matrices:

$$P_{\hat{d}} = \begin{pmatrix} P_{FF} & P_{FO} \\ P_{OF} & P_{OO} \end{pmatrix}.$$

Mean non-integration referring only to the points of the object is determined according to:

$$\theta_o^2 = \frac{\bar{d}_o^T P_{oo} \bar{d}_o}{h_o},$$

where h_o is a class of the matrix P_{oo}. The value d_o is determined according to:

$$\bar{d}_o = \hat{d}_o + P_{oo}^{-1} P_{oF} \hat{d}_F.$$

The test statistics that the stability of the points is tested with is:

$$F = \frac{\theta_0^{\ 2}}{\sigma^2}.$$

When the value of the test statistics is smaller than the critical value:

$$F \leq F_{1-\alpha, h_o, f},$$

a zero hypothesis is accepted, i.e. the conclusion is made that the points on the object are really stable. When the value of the test statistics is larger than the critical value, the alternative hypothesis is accepted, i.e. the points of the object are not stable.

2.2 The Analysis of Deformations according to the Karlsruhe Model

The essence of the Karlsruhe method is in independent adjustment of *zero* and *i*-th measurement series, and in their mutual adjustment (both series together). The deformation analysis is carried out by means of statistical testing of the general linear hypothesis and it is applied in the results of geodetic network adjustment for the purpose of identifying stable points. In the first phase, the observations in single measurement series are adjusted using the method of least squares, and in the second phase the mutual adjustment of *zero* and *i*-th measurement series is made. Mutual adjustment of two series is carried out providing as follows (Mihailović, Aleksić 1994; Savšek-Safić 2002):

- that the points are stable (the same coordinates) in two series,
- that the network scale is the same in both series and
- that the measurement accuracy is homogeneous in both series.

Adjustment of single measurement series is done by means of the method of least squares. After that, it should be defined whether the measurements are of equal accuracy in all series. Defining the homogeneity of measurements is made in the same way as it is done with the Hannover model, i.e. using F – test. German procedure of Karlsruhe method is carried out in several phases that make it possible for the stable points to be identified, and to determine the movements of unstable points with the reference to the stable points.

After defining the model needed for the adjustment of the network, the statistical testing of general linear hypotheses is done. In the first phase the measured values are adjusted, independently in each series using the method of least squares. From each single adjustment a square form is calculated:

$$\Omega_i = \left(v^T P v\right)_i, i = 1,2...,k,$$

where:

- k – is the number of measurement series.

Mutual square form for all series is obtained by adding the square forms from the adjustment of individual series:

$$\Omega_0 = \sum_{i=1}^{k} \Omega_i = \sum_{i=1}^{k} \left(v^T P v\right)_i.$$

The number of freedom degrees *b* is obtained by adding the number of freedom degrees from the adjustment in individual series:

$$b = \sum_{i=1}^{k} b_i,$$

where:

- b_i – is the number of freedom degrees of the i-th series $b_i = n_i - u_i$.

For the sake of simplicity we will consider only two series (zero and the first), i.e. $k = 2$:

$$\Omega_0 = \Omega_1 r_1 + \Omega_2 r_2 = \left(v^T P v\right)_1 + \left(v^T P v\right)_2 = v^T P v,$$

where:

- r_1 and r_2 are the relations of measurement weights in the zero and the first measurement series.

In the second phase the reference points are selected and the movements of unstable network points determined. It is achieved by testing the general linear hypothesis carried out after all networks have been adjusted (each series separately and both series together). The hypothesis reads as follows:

zero-hypothesis H_0	$E[l] = \hat{l} = Ax$, $Bx = d = 0$	points are stable,
alternative hypothesis H_A	$E[l] = \hat{l} = Ax$, $Bx = d \neq 0$	points are unstable,

where *d* is the difference of coordinates obtained from the adjusted *zero* and *i*-th series. In hypothesis testing there are also mathematical conditions included that need to be satisfied by the unknowns (coordinates of points). These conditions define the difference of coordinates obtained from the adjustment of *zero* and *i*-th series, for the stable points it should be zero ($d = 0$), and for the unstable points it should be different from zero ($d \neq 0$). If the differences of the coordinates of two series are not equal to zero, one should find out by means of statistical tests if these differences have occurred due to the measurements errors only, or due to the measurement errors and movements of points. In the first case the network points are stable, and in the second they are unstable. In mutual adjustment of two series, the vector of unknown coordinates consists of three sub vectors:

$$x^T = \left(z^T, x_1^T, x_2^T\right),$$

where:

- z – is the sub vector of ref. points that are supposed to be stable in both measurement series,
- x_1, x_2 – are sub vectors of points that are supposed to be unstable.

The sub vectors of the coordinates of fundamental points z^T, that are supposed to be stable, have the same unknowns in both series. The other points that are considered unstable have unknown coordinates in both series, i.e.:

$$\begin{aligned} x_1^T &= \left(x_1, x_2, \ldots\right) \\ x_2^T &= \left(x_1', x_2', \ldots\right) \end{aligned}.$$

From the square form of mutual adjustment ${v_z}^T P v_z$, that contains the information about measurement errors and information about the movements of unstable points the square form that contains the information about the measurement errors only should be subtracted:

$$\Omega_h = \Omega_z - \Omega_0 = {v_z}^T P v_z - v^T P v = v'^T P v' - v^T P v = (x' - x) Q^{-1} (x' - x),$$

$$v' = Ax - l, x' = x + dx, dx = x' - x, Q_x^{-1} = N = A^T P A,$$

where:

- dx – is the movement vector of unstable points in the direction of coordinates axes.

in the newly formed square form Ω_h, there will be only the information about the movements of unstable points, and it can be used for creating the test statistics that would show whether there are any unstable points in the set of presumably stable points.

The square forms follow χ^2 division:

$$\Omega_0 = v^T P v - \chi_b^2 \sigma_0^2,$$

with b freedom degrees for all measurement series, and therefore:

$$\Omega_h = \Omega_z - \Omega_0 = \left({v_z}^T P v_z - v^T P v \right) - \chi_f^2 \sigma_0^2,$$

with f freedom degrees for the *i-th* and *zero* measurement series:

$$f = (k - 1) \cdot n \cdot p_0 - d,$$

where:

- k – is the number of series encompassed by mutual adjustment,
- n – is a network dimension (n=1 for 1D network),
- p_0 – is the number of approximately stable points (of the fundamental network),
- d – free-network defect (1 - for 1D - network).

It is now possible to define the test statistics for on-dimensional geodetic network:

$$T = F_{f,b} = \frac{\chi_f^2 / f}{\chi_b^2 / b},$$

that follows F – division with f and b freedom degrees. Now we obtain that:

$$T = F_{f,b} = \frac{\Omega_h / f}{\Omega_0 / b} = \frac{\left({v_z}^T P v_z - v^T P v \right)}{v^T P v} \cdot \frac{b}{f}.$$

Thus calculated value test is compared with the value of F-division, calculated with the following parameters: $F_{f,b,1-\alpha}$, where α is the reliability level, and in this case α = 0.05. If $T \leq F_{f,b,1-\alpha}$, the test statistics T follows F central division, and accepts zero hypothesis H_0, which means that all points from the set of presumably stable points are really stable points. If $T \geq F_{f,b,1-\alpha}$, the test statistics T has got F non-central division, and the alternative hypothesis H_A is accepted, which means that all points from the set of conditionally stable points are not stable points, i.e. there are some unstable points among them. They should be separated from the set of conditionally stable points. F-test statistics can be used only if square forms Ω_h and Ω_0 are mutually independent.

Determination of unstable points in the set of presumably stable points

The test statistics offers global information about the stability of points listed in the set of presumably stable points. If $T \leq F_{f,b,1-\alpha}$, then all points in the set of presumably stable points are really stable points. Thus, the procedure of testing stable points is completed, because they have been completely identified. If $T \geq F_{f,b,1-\alpha}$, then there are unstable points in the set of presumably stable points, and it should be defined which points are unstable.

For this purpose mutual adjustments are repeated with one by one points excluded from them successively. There will be as many such adjustments as there are points in the set of presumably stable points, and in each of these adjustments one by one point will be excluded. The adjustment resulting in minimal value of square form $\Omega_{z_{\min}}$, indicates to the fact that the point excluded in adjustment should be considered an unstable point. It is definitely excluded from the set of presumably stable points, and the whole procedure is repeated without it. In the next iteration the next unstable point will be defined in the same way, and the procedure is thus repeated cyclically as long as the condition $T \leq F_{f,b,1-\alpha}$ is fulfilled.

The points remain in the set of presumably stable points after the condition $T \leq F_{f,b,1-\alpha}$ has been fulfilled, they are proclaimed stable points. Their coordinates from the zero series are adopted as given quantities, the current series is completely adjusted. The introduced hypotheses can serve for the purpose of checking the identified stable points by iterative procedure, and for the identification of unstable points on some object.

3. PRACTICAL APPLICATION OF DEFORMATION MODELS

The analysis of the deformations using the Hannover model has been made by means of the software *Panda* that uses this model as a theoretical basis. This is a multipurpose program package intended exclusively for geodetic profession. It contains a lot of functions and data, which makes it possible to solve various types of geodetic tasks more simply. *Panda is the software for adjustment of geodetic network and analysis of deformations* (Niemeier 1990).

The analysis of deformations using Karlsruhe model was made by applying the software *Matlab*. The program Matlab is used for solving various mathematical problems. Up to now the possibilities of Matlab have been very much increased as related to its original version of "matrix laboratory ". We are now speaking of interactive system and program language for general technical and scientific calculations. Matlab is created as a system as well in which its user can build in a very simple way his/her own tools and libraries and modify the existing program languages. This very characteristic of Matlab was used, and there was an algorithm made for the analysis of deformations using Karlsruhe model.

4. THE RESULTS OF COMPARING DEFORMATION MODELS

The Comparison of deformation models was made on the levelling network stabilized on the objects of the concrete factory Holcim d.o.o. in Koromačno needed in monitoring vertical movements of the silos for concrete storage (Fig. 1). Koromačno is a settlement in southeastern Istria, 19 km southwards from Labin, in the bay having the same name between the peninsula Ubac covered with forests in the west and the cape Koromačno in the east. The silo itself is placed in the Holcim factor Koromačno.

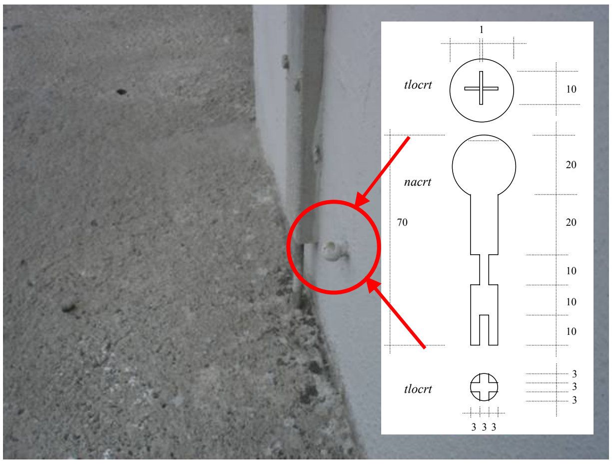

Fig. 1. Concrete silo **Fig. 2.** Stabilized bench mark with a plan

Local levelling network was developed for the silo in relative height system. The measuring spots on the object-bench marks (Fig. 2) were placed on the position according to the "Project of founding and securing the slope" (Fig. 3).

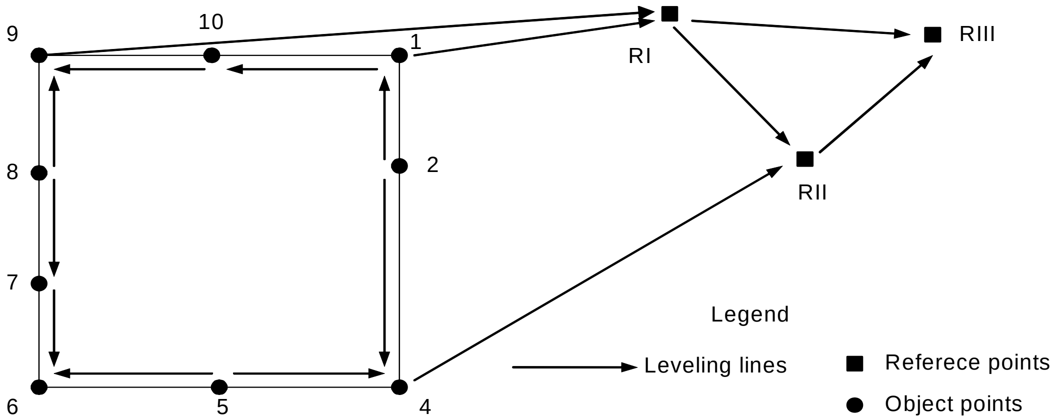

Fig 3. Test levelling network.

In all measurement series there were two independent measurements of all bench marks made in two direction, with the reading of two scales on the levelling staff , using the method of precise geometric levelling. The measurements were made with the precise level WILD NA2. In each series there were the same elevation differences measured (15 elevation differences in each series). The measuring data are shown in the following table

Table 1. Measuring data of the test levelling network.

Elevation difference		*Measurement series*			
From	*To*	*I series*	*II series*	*III series*	*D(m)*
RI	*RII*	0,5157	0,5156	0,5156	26
RII	*RIII*	0,5071	0,5071	0,5070	46
RI	*RIII*	1,0228	1,0229	1,0229	69
1	*RI*	0,4945	0,4948	0,4951	40
4	*RII*	1,0008	1,0009	1,0012	70
2	*1*	0,0178	0,0178	0,0177	4,8
2	*4*	0,0275	0,0275	0,0275	12,8
5	*4*	0,0283	0,0284	0,0282	8,9
5	*6*	0,0369	0,0368	0,0368	8,9
7	*6*	0,0128	0,0126	0,0142	5,4
8	*7*	0,013	0,013	0,0116	7,3
8	*9*	0,0243	0,0243	0,0240	5,3
10	*9*	0,0161	0,0164	0,0161	8,9
1	*10*	0,0008	0,0007	0,0008	8,9
RI	*9*	0,4777	0,4779	0,4783	57,8

Hannover method

Analysis of the series 1 - 2

Testing the homogeneity of measurements in two different series

$F = 2.24$

$F_{1-\alpha,f1,f2} = 6.4$

$F \leq F_{1-\alpha,f_1 f_2}$ ***- measurements are homogeneous.***

Global analysis of movements between two series

$F = 3.01$

$F_{1-\alpha,h,f} = 3.35$

$F \leq F_{1-\alpha,h,f}$ ***- no movement in the second series, all points are stable.***

Analysis of the series 1 - 3

Testing the homogeneity in two different series

$F = 3.03$

$F_{1-\alpha,f1,f2} = 6.4$

$F \leq F_{1-\alpha,f_1 f_2}$ ***- measurements are homogeneous.***

Global analysis of movements between two series

$F = 68.85$

$F_{1-\alpha,h,f} = 3.35$

$F \geq F_{1-\alpha,h,f}$ ***- there are movements in the third series of measurement, there are unstable points!***

Table 2. Value test of the Hannover method

Point	θ_i^2	max θ_i^2
1	$1,85*10^{-9}$	
2	$7,57*10^{-10}$	
4	$7,01*10^{-10}$	
5	$1,12*10^{-9}$	
6	$1,03*10^{-7}$	
7	$3,15*10^{-7}$	max
8	$9,47*10^{-8}$	
9	$7,10*10^{-9}$	
10	$8,25*10^{-41}$	

The movement of the points 7 has been defined. After removing the point 7 from the set of points, we determine by means of test statistics whether there are any more unstable points.

$F = 3.94$
$F_{1-\alpha,h,f} = 3.31$
$F \geq F_{1-\alpha,h,f}$ - ***there are still some movements in the third measurement series, there are unstable points!***
We calculate the value test again, now for the remaining 8 points.

Table 3. Value test after excluding the point 7

Point	θ_i^2	max θ_i^2
1	$1,85*10^{-9}$	
2	$7,57*10^{-10}$	
4	$7,01*10^{-10}$	
5	$1,12*10^{-9}$	
6	$9,84*10^{-11}$	
8	$7,64*10^{-9}$	max
9	$7,10*10^{-9}$	
10	$8,25*10^{-41}$	

The movement of the point 8 has been defined. After removing the point 8 from the set of points, we determine by means of test statistics whether there are any more unstable points.
$F = 2.98$
$F_{1-\alpha,h,f} = 3.31$
$F \leq F_{1-\alpha,h,f}$ - ***there are no more movements in the third series of measurement, all other points are stable!***
By means of Hannover method the movements have been defined in the points 7 and 8 with 95% probability.

<u>Karlsruhe method</u>
Analysis of the series 1 - 2
The testing of the homogeneity of measurements in two different series is made in the same

way as with the Hannover model. Hence, the measurements are homogeneous.

Global analysis of movements between two series
$T = 3.06$
$F_{11,8,0.95} = 4.05$
$T \leq F_{f,b,1-\alpha}$ ***- there are no movements in the second series of measurements, all points are stable.***

Analysis of the series 1 - 3
The testing of the homogeneity of measurement in two different series is made in the same way as with the Hannover model. Hence, the measurements are homogeneous.

Global analysis of movements between two series
$T = 68.85$
$F_{6,8,0.95} = 4.05$
$T \geq F_{f,b,1-\alpha}$ ***- there are movements in the third series of measurements, there are unstable points!***

Table 4. Value test of the Karlsruhe method

Point	Ω_Z	Ω_Z min
1	$3,31*10^{-7}$	
2	$3,37*10^{-7}$	
4	$3,34*10^{-7}$	
5	$3,35*10^{-7}$	
6	$1,54*10^{-7}$	
7	$2,11*10^{-8}$	min
8	$1,94*10^{-7}$	
9	$3,11*10^{-7}$	
10	$3,37*10^{-7}$	

After the first iteration we remove the point 7. Using test statistics we test whether there are more unstable points left.
$T = 5.23$
$F_{6,8,0.95} = 4.05$
$T \geq F_{f,b,1-\alpha}$ ***- there are still some movements in the third series of measurements, there are still unstable points present!***

The network where the analysis was made consists of 12 points that are connected with 15 measurements (n=15, u=12). After the first iteration using the Karlsruhe method, there were two measurements (n=13, u=11) removed from further analysis along with excluding 7 points. Since in the repeated mutual adjustment on point at the time is excluded alternatively using the Karlsruhe method, we can conclude that leaving out e.g. 9 points from the adjustment, 3 additional measurements would be left out. Then we would have 10 measurements and 10 unknowns (n=u=10), i.e. the adjustment is not possible. Due to the lack of redundant measurements, further analysis using Karlsruhe method is not possible. The lack of redundant measurement has appeared because of the specific position of the silos. The points 5,6,7 and 8 are placed in the cutting, and it was not possible to connect additional measurements.

5. CONCLUSION

In the first part of this work there are some theoretical elements of the deformation analysis according to the Hannover and Karlsruhe models presented. In the second part the application of deformation models is presented on the example of the test levelling network stabilised for monitoring the movements and deformations of silos for concrete storage in the factory Koromačno. The analysis of deformations using Hannover and Karlsruhe models should have discovered whether there were some movements appearing, and whether these methods yield the same results.

The deformation analysis according to both model has discovered that the measurements of all series are homogeneous and that it is possible to start analysing the deformation. Further, global movement test had to be done for the second and third series. It has been found out that there is a movement in the third measurement series according to both models. Finally, the movement needed to be localized, i.e. the point needed to be defined where the movement appeared. Both models have localized the point No. 7 as an unstable point, i.e. the point where the movement appeared. Hannover model has shown the movement of point 8 as well, and the analysis of the deformations using Karlsruhe model was not possible due to the lack of redundant measurements. All other points are stable.

It can be concluded that both deformation models are practical for discovering the movements of objects, but the presented example has shown that Hannover model has proven to be more acceptable. Namely, due to the configuration of the network caused by terrain circumstances, which caused insufficient number of redundant measurements, the deformation analysis using Karlsruhe model was not as efficient as the one using Hannover model.

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